HISTORICAL BACKGROUND AND DEVELOPMENT OF THE CHARPY TEST

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ABSTRACT

The impact test method based on a pendulum, generally called the Charpy test, is one of the more cost-effective material testing procedures, both with respect to acceptance of products and to surveillance. This contribution attempts to present a brief historical review about the general development of material testing, starting at the beginning of the intense industrialisation in the second half of the 19th century, and tries to point out the role and the position of impact testing during this period. Several periods in the evolution of impact testing based on a pendulum are discussed in detail.

KEYWORDS

Charpy impact testing, history of material testing, instrumented impact testing, pendulum impact testing

INTRODUCTION

It has been said (Harvey, 1984) that "No man is civilised or mentally adult until he realises that the past, the present, and the future are indivisible." This statement applies equally to all fields of science and technology, including material testing.

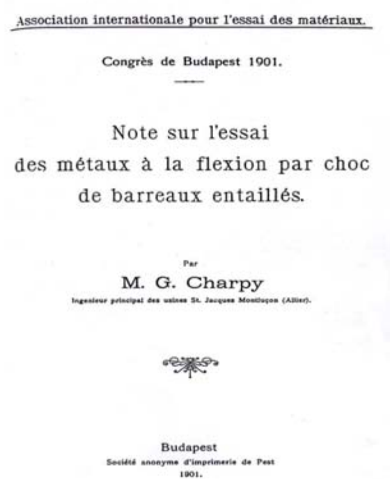
This contribution focuses on the development of material testing using the Charpy test method, which is based on the use of a pendulum to apply an impact force to a specimen. Some of the milestones in the development of this technique have been outlined in a recent conference on *Fracture Mechanics in Design and Service - Living with Defects* by the Royal Society in 1979, where the important role of the impact pendulum test machine was highlighted. The present history-oriented contribution illuminates the development of impact testing from a material toughness characterisation point of view.

Historically, the impact-pendulum test method and associated apparatus were suggested (in nearly their current forms) by S. B. Russell in 1898 (Russell, 1898) and G. Charpy in 1901 (Charpy, 1901a, b). A. G. A. Charpy (Fig.1) presented his fundamental idea in France in the June issue of the Journal of the Soc. Ing. Civ. de Francais and in the Proceedings of the Congress of the International Association for Testing of Materials, which was held in Budapest in September 1901 (see Fig.2.) The impact-test procedure seems to have become known as the Charpy test in the first half of the

1900’s, through the combination of Charpy’s technical contributions and his leadership in developing the procedures to where they became a robust, engineering tool.

The consideration of material behaviour in the design of different types of construction that operate at very different conditions is as old as the material test procedures themselves, because the science

Figure 1
Augustin Georges Albert Charpy
Born 1 September 1865 in Ouillis, Rhone
Died 25 November, 1945 in Paris



Association internationale pour l'essai des matériaux.

Congrès de Budapest 1901.

Note sur l'essai
des métaux à la flexion par choc
de barreaux entaillés.

Par
M. G. Charpy
Ingenieur principal des usines St. Jacques Montluçon (Allier).

Budapest
Société anonyme d'imprimerie de Pest
1901.

Figure 2
Title page of Charpy’s paper
at the VIIth Congress of the International Assoc. For Testing of Materials in Budapest, 8-13 September 1901

and technology of failure prevention is intimately associated with failures and accidents. From this, it follows that the development of new material-testing procedures occurred in close connection with the history of engineering science. It is unfortunate that many engineers still derive a large body of their knowledge from accidents, although *learning from failures and accidents* is regarded as the most costly way to improve one’s skills and technologies.

The early development of material testing was driven by the rapid expansion of the railway network between about 1830 and 1900. Figures 3 and 4 compare the development of the railway network in Germany and in the whole world. The world’s first public railway was opened in northern England

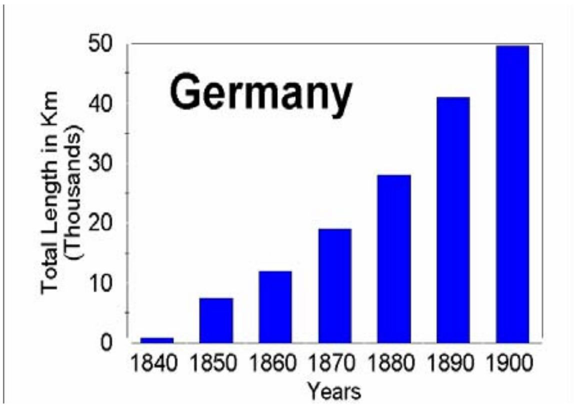


Figure 3. The growth of railway network in Germany

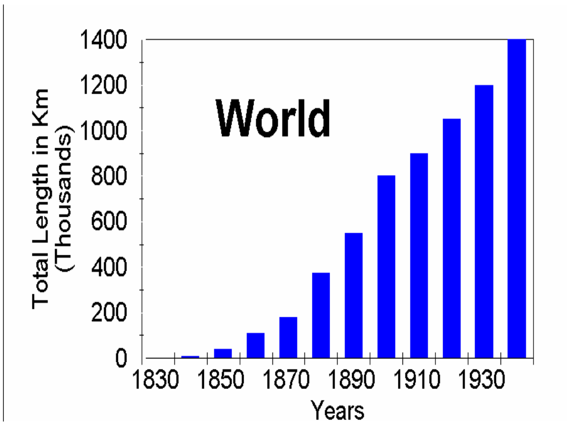


Figure 4. The growth of railway network in the world

between Stockton and Darlington on 27 September 1825, whereas the first public railway in Germany was operated on June 12 in 1835 between the city of Nuremberg and the neighbouring city of Fürth. The first railroad in the U.S., the Baltimore and Ohio, began in 1828 serving Baltimore and points west, and by 1835, Boston was the first railroad hub in the U.S., serving as the terminus of three railroads. In the territory of present Hungary, the first railway line (39 km) was installed on July 15, 1846 connecting the cities of Budapest and Vác. The situation was similar in most other countries, and by 1900 there was an extensive railway network serving most of Europe. By 1900, the total length of railway network in the world was in excess of 800.000 km, with an annual increase of more than 10.000 km (a quarter of the circumference of the globe).

The development of all aspects of engineering science during this time was strongly motivated and promoted by the rapid expansion of the global railway network, through the enormous demand for rails, locomotives, cars, tunnels, bridges, dams, railway stations and other mechanical and civil engineering structures. In the field of material testing and behaviour, a basic understanding was developed of the load-carrying capacity of a component and its critical fracture stress.

The characterisation of brittle and ductile behaviour of materials, as well as the clarification of the ductile-brittle transition behaviour of metals, was driven by the large number of failures of rails and axles that began to catch people's attention during the 19th century in all industrialised countries. As early as 1836 or 1838, Stendhal, a French writer, mentioned a serious problem related to fatigue damage in his novel "Mémoires d'un touriste". Unexpected and unexplained breakages continued to increase between 1840 and 1860. Most of these failures caused catastrophic accidents without any warning because they were brittle failures, i.e., the fractures were not preceded by noticeable plastic deformation to serve as a warning of incipient fracture.

The situation because still more serious when it was found that machine components could also fail at stress levels well below the critical fracture stress. All that was necessary for this type of failure to occur was the presence of cyclic load fluctuations, either random or periodic. It was observed (although the reason was not understood until later) that a fracture would originate and initiate at certain locations and slowly, then more rapidly, propagate into the material and finally rupture the component, most often in a brittle fashion. Thus, a new type of failure, *fatigue*, was identified. Once it was recognized that fatigue damage propagated by the growth of a sharp crack through a component, a variety of notch configurations were added to specimens to evaluate how their performance was degraded by such damage. A contributing factor to the rapid rise in unexpected failures was the increase in the use of metals, instead of the construction materials (wood, brick, stone, etc.) previously used, for which design guidelines, service history, and maintenance procedures were well known. The relative use of metals for construction changed from approximately 20 % at the beginning of the industrial revolution to about 80 % at the turn of the last century.

Material testing procedures were developed to collect information about the behaviour of various materials, predominantly metals, operating at different external conditions. This information was then processed to characterise these materials for engineering purposes.
This, in turn served as the driving force for:

- the general development of engineering science, especially the disciplines of mechanics and strength of materials;
- the construction and manufacture of large engineering structures (such as bridges, ships, steam engines, railway stations, towers.);
- the development, in materials science, of new types of materials, metals, steel-producing technologies, etc.;
- the appearance of new disciplines (metallography, description of the different types of metallurgical processes, micro-structures, etc.);

- the appearance of new material testing methods, procedures, equipment, etc.

During the second industrial revolution in the 19th century, England and Germany played dominant roles. A major part of the research efforts in these two countries was focused on developing an understanding of unexpected fracture failures. Top priority was devoted to avoiding, or at least limiting and controlling these unexpected failures (Braithwaite 1853; Mann 1970; Rankie 1843; Rolt 1970; Schütz 1970; Wöhler 1858). Ever since, there has been a steady stream of results, experiences, new developments and inventions in the field of fatigue in the leading technical journals (Bauschinger 1896; Kirkaldy 1862; Paris 1982; Rossmanith 1997; Sedov et al 1972; Timoshenko 1953). The importance of the subject can best be appreciated by the rapid increase of technical papers associated with fatigue failures, as shown in Fig 5.

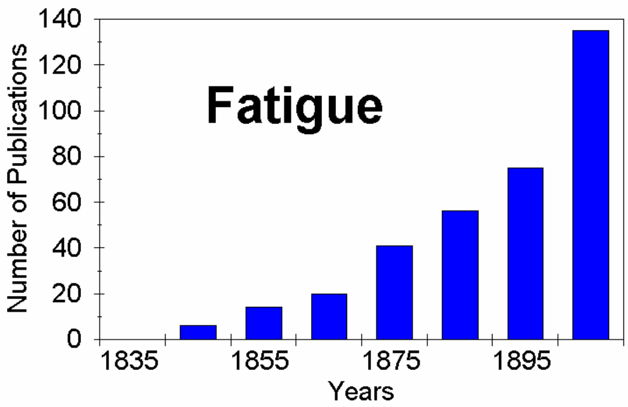


Figure 5. Total number of publications related to fatigue failures in the 19th century

In spite of the huge efforts being applied towards eliminating the failures that take place under conditions of general yielding, there was no generally accepted and agreed-upon method of testing for the characterisation of ductile and brittle material behaviour of metals over a range of working conditions. Unexpected and unexplainable failures of rails, axles, etc. were observed all around the world. As a result of this, a new type of material – steel – was developed around the middle of the 19th century, new testing equipment was created, and new, independent (private) testing laboratories emerged. In 1858, D. Kirkaldy was the first to open a private public material testing laboratory in Southwark in London and developed a quality seal for his test documents, to differentiate his measurements from those developed with older procedures. Kirkaldy also suggested the introduction of the *true stress at the moment of fracture* and *percentage reduction of area* as quantities most useful for the characterisation of metals subjected to tensile loading. The results of various test methods performed in the Kirkaldy testing works were summarised in an excellent book (Kirkaldy, 1862) and his conclusive remarks were fully supported by the experiments. Todhunter and Pearson (1886), in their three-volume treatise on the development of elasticity and materials testing, frequently refer to Kirkaldy's work, but do not mention the behaviour of materials under dynamic loading conditions.

Within the development of materials testing, the following important milestones can be identified:

- the development of fatigue testing techniques,
- the founding of research institutes and testing laboratories,
- the observation and clarification of the nature of metal fatigue,
- the determination of material properties that can be used for elimination (decrease of risk) of fatigue of railway axles,
- the development of new steel-making technologies,
- the founding of the first private material-testing laboratory,

- the development of tensile test methods for the characterisation of material behaviour.

Table 1 in Appendix A features a partial sequence of selected important events in the historical development of materials testing.

EVOLUTION OF THE MATERIAL TESTING COMMUNITY

While metals were gaining increasing importance in engineering, two needs became apparent:

- mechanical engineers wanted to determine the behaviour of metals with respect to a variety of external working conditions, and
- a strong demand was developing for unifying the various proposed material characterisation procedures, as a way of accurately defining shipping and acceptance conditions.

Both needs served as excellent bases for the organisation of specialist meetings. Johann Bauschinger in Munich was the first to clearly recognise this opportunity and organised the first of a series of (so-called *Bauschinger) Conferences* in Munich in 1884 with a participation of 79 specialists from all over the world. The second *Bauschinger Conference* was organised in Dresden in 1886, the third one in Berlin in 1890, and the last one, the fourth in Vienna in 1893, just before his death. The translation of the proceedings of the *Bauschinger Conferences* into English and publication by the U.S. Government Printing Office in Washington D.C. reflect the importance of these conferences. A group of material testing experts, derived from the attendees at the Bauschinger Conferences, participated at the World Exhibition in Paris in 1889. This team was a technical committee of the “Applied Mechanics Section” and was led by Johann Bauschinger. The need for international co-operation and organisation in the field of material testing became immediately clear. In reality, the *Bauschinger Conferences* had already enjoyed an international character, a fact that was noticed in the *Resolutions of the Conventions* held at Munich, Dresden, Berlin and Vienna (Bauschinger 1896):

> *“Not only has there been an increase in the number of delegates from countries already represented (Germany, Austria-Hungary, Switzerland, Russia), but delegates have come from other countries (France, America, Norway, Holland, Italy, Spain), so conventions have assumed a truly international character”.*

The sudden death of Bauschinger in 1893 left the job of founding a new international association to Ludwig von Tetmajer (born 14 July 1850 in Krompah, Austrian-Hungarian Empire, died 31 January 1905 in Vienna) who had previously founded the Eidgenössische Materialprüfungs-Anstalt (EMPA) in Zurich and was serving as director at the time. He took over the responsibility of continuing the *Bauschinger Conferences* and, during the conference that he organised in Zurich during the period 9 to 11 September 1895, founded the *International Association for Testing of Materials* (IATM). This conference is regarded the “first” international conference on material testing. If the previous Bauschinger Conferences are included, the Zurich Conference is the 5th *Bauschinger Conference*. The international conferences of the *International Association for Testing of Materials* were held periodically: 1897 in Stockholm, 1901 in Budapest, 1906 in Brussels, 1909 in Copenhagen, 1912 in New York, 1915 in St. Petersburg, and 1927 in Amsterdam. After World War I, the association lost its technical focus and became much more political. Mirko Ross, who served as director of the EMPA, re-established the society now named *New International Association for the Testing of Materials = Neuer Internationaler Verband für Materialprüfungen = Nouvelle Association Internationale pour l’Essai des Matériaux*. The new organisation held its first conference during 11 to 16 September 1931 in Zurich; the proceedings of this meeting, however, were published one year earlier (!) in 1930 (Rosenhain 1930).

EVOLUTION OF IMPACT TESTING

The evolution of impact testing may be divided into the following four periods:

- Early developments: up to the time of standardisation of testing procedures,
- The stage of brittle fracture: period up to the beginning of the 1950s including the brittle-fracture story and the transition-temperature concepts (Liberty ships),
- The development of fracture mechanics: up to the early 1980s including the correlation between the absorbed energy measured with CVN and other fracture-mechanics parameters, (covered in other papers in this publication)
- The current stage: including instrumented impact testing, testing on sub-size specimens, etc. (covered in another keynote lecture)

Early Developments in Impact Testing

The question "How can the results of static and dynamic material tests be correlated?" was not addressed in the first edition of the book by Kirkaldy in 1862. Questions of this kind were first raised only later in the 19th century. In his 1901 paper, Charpy noted that the lack of correlation between the static and dynamic testing results may have been addressed for the first time by Mr. Lebasteur in his book *Les métaux á L'exposition de 1878.* Impact testing of rails using the drop-weight test method had become an unofficially accepted standard method in Germany. This is noted in the *Resolutions of the Conventions held at Munich, Dresden, Berlin and Vienna* (see paragraph 10 of the General Provisions: 13-16).

The status of impact-testing technology was summarised in the International Association for Testing of Materials *Steering Committee Report for the period of 1879-1901* by L. Tetmajer. In the following years, the characteristic features of the impact-testing procedure continued to be developed by specialists in IATM, and their reports were discussed at the conferences held following 1901. The development of consistent impact procedures was recognized to be of such importance by about 1905 that the impact testing activities were taken out of Committee 22 (on uniform methods of testing materials), and used as the basis for a new committee, Committee 26 (with impact testing as its only focus). The meetings brought a truly international group of experts to a single location, facilitated the exchange of ideas, and allowed the formulation of research plans for reports at the next meeting. Also, by 1905, Charpy had proposed a machine design that is remarkably similar to present designs, and the literature contained the first references to "the Charpy test" and "the Charpy method".

A.G.A. Charpy became the chair of the impact-testing activity after the 1906 IATM Congress in Brussels, and presided over some very lively discussions on whether impact-testing procedures would ever be sufficiently reproducible to serve as a standard test method. The activities within IATM at this time are covered in more detail in the following paragraphs because this is the period in which the Charpy test developed substantially into its present form, under the able leadership of A. G. A. Charpy. The discussions centred around the importance of the geometry of the notch (depth, root radius), impact velocity, specimen size, and the possibilities of practical application of the impact testing (i.e., transferability of results to machine parts, life predictions, etc.). Highlights of these meetings included:

a) *Report by A.G.A. Charpy at the Brussels Conference in 1906:*

- The pendulum impact test method was being used by the National Marine for testing of armour plate,

- Boiler steels tested and the testing results published by Yarrow et al. in the *Journal of Engineering* on 18 April 1902; the main conclusion of the paper was that the Charpy test method could be employed to categorise the notch toughness (or conversely, the brittleness) of boiler steels.
- Two types of pendulum impact machines have been accepted:

  Machine type 1 was characterised by the impact velocity of 7,8 m/s and the impact energy level of 200 kg-m (approximately 2000 J);

  Machine type 2 was characterised by the impact velocity of 5,28 m/s and the impact energy level of 30 kg-m (approximately 300 J).
- Two types of notches were in use: sharp notches and rounded ones.
- The effect of impact velocity was investigated by dropping the striker from various heights: 3.3 m, 2.3 m and 1.1 m. The dynamic drop test results were compared with those of quasistatic bending tests. It was found, that the effect of impact velocity on the absorbed energy was much higher in the case of sharply notched specimens.
- A Technical Committee was established for analysing the results of Charpy tests. The members included Martens, Stibek, Lasche, and Ehrensberg.

b) *Report by A.G.A. Charpy at the Copenhagen Conference in 1909:*

- the discussion of the Report of the Technical Committee mentioned above (published by E. Ehrensberger) during the meeting of the German Material Testing Association on 5 October, 1907 (republished in Stahl und Eisen, 50 and 51, 1907, (Blumenauer)).
- The current state of practical use of impact testing was reviewed, discussed and reported in different countries. The report by Simonot (1907) was discussed at the common meeting of the French and Belgian members of ISTM on 1 June 1907. Breuill (1908) published a paper on material testing procedures in the Revue de Mechanique. In England, Stanton and Baristow (1908) reported in the Institution of Mechanical Engineers on impact testing of metals and Harbord (1908) reported on impact testing methods using notched specimens.
- The experiences of Hatt published by ASTM in 1904 were analysed.
- An intense discussion developed about the topic of ductile-brittle phenomena.
- The effect of strain rate on the behaviour of metals was discussed.
- Requirements for impact testing machines were defined.
- The information content of impact testing was analysed.
- Different kinds of practical applications were reported (naval applications, metallurgical plants, engineering works, etc.).

c) *Report by A.G.A. Charpy at the New York Conference in 1912:*

- A Technical Committee was formed in 1910, composed of international experts
- Two types of specimens were suggested:
  - ⇒ 30x30x160 mm^3 with a notch depth of 15 mm, notch root radius of 2 mm and span length of 120 mm;
  - ⇒ 10x10x53 mm^3 with a notch depth of 5 mm, a notch root radius of 0,6 mm and a span length of 40 mm.
- Experiments conducted by Charpy, Ehrensberger and Bartel showed a size effect: the specific absorbed energy (kgm/m^2) was larger for smaller specimens.
- The law of similarity for the behaviour of different specimen sizes was accepted. It was published in the following journals: Memorial de l'Artillerie Navale Francaise, 10, 11, and 12/1910 and Revue d'Artillerie Francaise, 7/1911. (It is interesting to note that, later in 1921, Stanton and Batson conducted tests featuring the breakdown of the law of similarity in notched-bar impact tests! (Stanton et al. 1921)).

- The requirements of the impact-testing equipment and machines to assure comparability of the testing results were discussed. The Commission proposed establishing a standard impact procedure that would assure that the results produced by two separate machines are comparable. Some of the procedural details that they proposed to control included:
    - ⇒ the depth and radius of the notch,
    - ⇒ limits on the velocity of the striker,
    - ⇒ a minimum ratio of anvil mass to the mounting base (to reduce vibrational losses),
    - ⇒ recognition of the need to limit frictional losses, and
    - ⇒ recognition of the artificial increase in energy as ductile specimens deform around the edges of a wide striker.
- The Technical Committee recommended that the following topics be discussed at the next IATM conference:
    - ⇒ comparability of the testing results
    - ⇒ establishment of a database with respect to technical parameters of the existing impact testing machines
    - ⇒ definition of possible fields of application for impact testing.

Charpy's drive toward standardization and practical application of the impact test procedure are revealed in some of his comments in the later IATM reports, such as (A.G.A. Charpy , 1912). Near the beginning of this report to the IATM leadership and to the other Committees, he reiterates the main goals of Committee 26 as to "fix the conditions to be fulfilled by two distinct tests in order that the results may be comparable and to correlate these numerically definite results to the qualities determining the practical values of a material for different uses". Toward the end of the report, Charpy made his view of the situation even more clear.

> *"Consequently, ...the investigation of the conditions which the impact testing machines should fulfill in order that they may furnish comparable results, should commence with the establishment of a method of standardization and verification..."*

While Charpy continued to guide the work in IATM, until at least 1914, much was happening within individual countries and at machine manufacturers. A number of machine designs and procedures were under consideration at this time, and in 1907 the German Association for Testing Materials adopted one developed by Ehrensberger (1907). Because the pendulum machine had not yet achieved dominance, designers and manufacturers of impact machines offered three major types; Drop Weight (Fremont, Hatt-Turner, and Olsen), Pendulum Impact (Amsler, Charpy, Dow, Izod, Olsen, and Russell), and Flywheel (Guillery). By 1909, there was broad recognition of a difference between static and dynamic loading, but little understanding of how to measure it, or even what to call it (fragility? resilience?).

Meanwhile, national chapters of the IATM were being formed in countries or countries were organizing separate standardization societies, apparently because the international Congresses met too infrequently to bring about the desired progress on the development of procedures to meet pressing national needs. A national standardisation institution was founded in Germany in 1896. In 1898, the national chapter of IATM in the U.S. became the nucleus for the American Society for Testing and Materials (ASTM). These organizations worked in parallel with IATM and other national organizations to standardise the Charpy impact test procedure. Unfortunately, the different groups chose some slightly different approaches to meeting the standardization needs. As a result of many such choices by the different standards organizations over the years, we now find some remaining variation in impact test procedures around the world. Certainly, world-wide comparison of test data would be simplified if the procedures could be further harmonized between countries and between the various standards.

The rapid development of impact testing around the turn of the last century is documented in a bibliography on impact tests and impact testing machines by Hatt and Marburg published in the 1902 Volume of the Proceedings of ASTM. This bibliography listed more than 100 contemporary papers on impact testing published in the U.S., France, and Germany. Supporters of some of the different machine and specimen designs participated in the different standardization groups, leading to the variations between the standards mentioned above.

Meanwhile in Germany, the extensive report by E. Heyn (1901) concerning the presentation by A.G.A. Charpy at the Budapest Congress on Materials Testing in 1901, led to the establishment of a comprehensive program by the *Deutscher Verband für Materialprüfungen der Technik* to evaluate the facilities for notch impact bending testing (1901). A detailed review of the activities on the new Charpy method during the first three decades of the 20th century was prepared by F. Fettweis (1919). The difficulty in harmonising the different procedures is clearly reflected in the German Encyclopaedia on Material Testing edited and published in 1961, where 27 types of impact specimens are still mentioned.

However, even while the procedural details were under discussion, the Charpy impact test was demonstrating its value in reducing the risks of service failures in components. In 1912, Derihon reported that factories in Liege and Jeumont were performing 10,000 impact tests each month. They were able to correlate the components that gave brittle results to various attributes of the steel: the composition (especially high levels of phosphorus and sulphur), casting defects (especially piping), and heat treatments. After revising their production procedures and acceptance criteria, they were able to reduce the amount of material rejected due to brittleness in the impact tests from as much as 40 % to only 0.3 %.

Serious work on standardising the procedures resumed after World War I. ASTM Committee E-1 on Methods for Testing sponsored a Symposium in 1922 on Impact Testing of Materials as a part of the 25th Annual Meeting of the Society, in Atlantic City, New Jersey. The Preface of the Symposium lists the goals as *"study the impact testing of materials more definitely and intensely…considering not only the details of methods…and possible standardization of methods, but inquiring into the true significance of the impact test…and the applicability of the data obtained to problems of engineering design and construction."* The Symposium included a history of the developments in this area, a review of work done by the British Engineering Standards Association, and several technical presentations.

Also at this symposium, Warwick presented the results of a survey sent to 64 U.S. testing laboratories. Twenty-three respondents to the survey offered detailed information on topics such as the types of machines in use, the specimen dimensions, and procedures. In addition, many responded positively to a question about their willingness to develop an ASTM standard for impact testing.

The group interested in developing an ASTM Standard Procedure finally published a tentative procedure, E 23-33T, in 1933. As experience was developed with the tentative procedure, the group continued to make revisions. The minutes of the 1939 and 1940 meetings for the Impact Subcommittee of E-1 state that the striker radius was discussed, and a survey was made of the geometries used in the United Kingdom and in France. Those countries were found to be using radii of 0.57 mm and 2 mm, respectively. For reasons that were not recorded, the members of the Subcommittee agreed to a radius of 8 mm at the 1940 meeting and ASTM E 23 was revised and reissued as E 23-41T. Two other changes that occurred with this revision were that metric units became the preferred units, and keyhole and U notches were added for Charpy test specimens.

Similar discussions were occurring in standardisation bodies around the world in the 1930s and 1940s, although the exact dates of certain changes to the impact testing procedures in the some countries could not be located. The discussions included the types of specimens (Charpy U, Charpy keyhole, Izod, etc.), the testing method (Charpy or Izod) and the geometry of the striking edge (i.e. the geometry of the striker or *tup*). Although many contradictory opinions were put forward at these discussions, standardised testing procedures were established.

Evolution of the Impact Testing up to the Beginning of the 1950s

Impact testing seems to have been adopted for internal use by some organisations around the world, but was not a common requirement in purchase specifications and construction standards until the recognition of its ability to detect the ductile-to-brittle transition in steel. Probably the greatest single impetus toward implementation of impact testing in fabrication standards and material specifications came as a result of the large number of failures in Liberty ships (a U.S. design) that occurred during World War II. These fractures occurred without any remarkable plastic deformation. Understanding the circumstances and elimination of these failures became a national effort during the war and a large research project was launched where impact testing was found to reveal a brittle-ductile transition behaviour of steels. These problems were so severe that the Secretary of the U.S. Navy convened a Board of Investigation to determine the causes and to make recommendations to correct them. The final report of this Board stated that of 4694 welded-steel merchant ships studied from February 1942 to March 1946, 970 (over 20 %) suffered some fractures that required repairs (Anon 1947). The magnitudes of the fractures ranged from minor fractures that could be repaired during the next stop in port, to 8 fractures that were sufficiently severe to force abandonment of these ships at sea. Remedies included changes to the design, changes in the fabrication procedures and retrofits, as well as impact requirements on the materials of construction. The time pressures of the war effort did not permit thorough documentation of the effect of these remedies in technical reports at that time; however, assurance that these remedies were successful is documented by the record of ship fractures that showed a consistent reduction in fracture events from over 130 per month in March 1944 to fewer than 5 per month in March 1946, even though the total number of these ships in the fleet increased from 2600 to 4400 during this same period (Anon 1947).

After the war, the U.S. National Bureau of Standards released its report on an investigation of fractured plates removed from some of the ships that exhibited these structural failures and so provided the documentation of the importance of impact testing (Williams et al. 1948). The NBS study included chemical analysis, tensile tests, microscopic examination, Charpy impact tests, and reduction in thickness along the actual fracture plane in the ship plates. A notable conclusion of the report was that the plates in which the fracture arrested had consistently higher impact energies and lower transition temperatures than those in which the fractures originated. This was particularly important because there was no similar correlation with chemical composition, static tensile properties (all steels met the ABS strength requirements), or microstructure. In addition, the report first established 15 ft-lb (often rounded to 20 J for metric requirements) as a minimum toughness requirement, and recommended that "some criterion of notch sensitivity should be included in the specification requirements for the procurement of steels for use where structural notches, restraint, low temperatures, or shock loading might be involved", leading to a much wider inclusion of Charpy requirements in structural standards.

This characterisation of the ductile-brittle behaviour of steels led to the inclusion of impact requirements in codes and standards, and then to a more detailed understanding of the fracture phenomena. Consequently, the relevance of the parameters on the *transition temperature* determined by Charpy tests was systematically investigated.

By 1948, many users of the ASTM Standard on impact testing thought that the scatter in the test results between individual machines could be reduced further, so additional work was started to more carefully specify the test method and the primary test parameters. Much of the work that showed that impact tests did not have inherently high scatter, and could be used for acceptance testing, was done (Driscoll 1955) at the Watertown Arsenal. Driscoll's study set the limits of 1 ft-lb (1.4 J) and ± 5 % for individual machines. Driscoll's work showed the materials testing community that not all machines in service could perform well enough to meet the indirect verification requirements, but that most impact machines could meet the proposed requirements if the test was conducted carefully and the machine was in good working condition. With the adoption of verification testing, it could no longer be convincingly argued that the impact test had too much inherent scatter to be used as an acceptance test.

Early results of verification testing showed that 44 % of the machines tested for the first time failed to meet the prescribed limits, and it was thought that as many as 50 % of all the machines in use might fail. However, the early testing also showed that the failure rate for impact machines would drop quickly as machines with good designs were repaired, machines with bad designs were retired, and more attention was paid to testing procedures. It was estimated that approximately 90 % of the machines in use could meet the prescribed limits of ± 1 ft-lb (1.4 J) or ± 5 %.

By 1964, when the ASTM E 23 standard was revised to require indirect verification testing, the primary variables responsible for scatter in the test were well known. In a 1961 paper, Fahey summarised the most significant causes of erroneous impact values as follows: (1) improper installation of the machine, (2) incorrect dimensions of the anvil supports and striking edge, (3) excessive friction in moving parts, (4) looseness of mating parts, (5) insufficient clearance between the ends of the test specimen and the side supports, (6) poorly machined test specimens, and (7) improper cooling and testing techniques. While the machine tolerances and test techniques in ASTM E 23 addressed these variables, it was becoming apparent that the only sure method of determining the performance of a Charpy impact machine was to test it with standardised specimens (verification specimens).

Meanwhile, in the 1950s, it was recognised that a more accurate understanding of the dynamic fracture process could be achieved only by instrumenting the pendulum machine and, thus, determine force vs. deflection / time records. The product between the rate of deceleration and the mass of the hammer resulted in values for the impact force. In the world's first commercial instrumented impact testing machine (called PSWO) manufactured by Werkstoffprüfmaschinen Leipzig in Germany (Siebel 1958), the impact load was measured by a piezoelectric sensor attached behind the striker. An oscillograph that was triggered by a photocell recorded the output signal from the sensor and a flag fixed to the pendulum. The same kind of instrumentation was also used for a rotating impact machine (RSO), which allowed test velocities up to 100 m/s.

During the following years, various committees were busily engaged with the determination of experimental requirements and procedures for valid evaluation of test data. The results were documented in two specifications (Anon. 1986; Anon 1987) that formed the basis for the ISO standard 14556 *Charpy V-notch pendulum impact test - instrumented test method* (German version DIN EN ISO 14556). Using these specifications, a DVM-Group on *Instrumented impact testing* performed a round robin test series with about 400 instrumented Charpy tests to compare the accuracy of the measurements (Böhme & Klemm 1993). The instrumented Charpy test on pre-cracked (and partly side-grooved) specimens (PICHT) opened the way to evaluate fracture mechanics parameters relevant to initiation and growth of cracks at higher loading rates. The influence of dynamic effects was analyzed by J. F. Kalthoff (1985) who developed the concept of *impact response curves* for measuring the impact fracture toughness K_{Id}. This concept extends the conventional quasi-static evaluation procedure into the low time-to-fracture range. The PICHT has been widely used to characterize the toughness of metallic and nonmetallic materials in research as well as in the industrial quality management. An essential step towards the applicability for accurate analysis of component safety has been reached by numerical simulation in combination with micro-mechanical material models.

Today the procedure of fracture-mechanics-based instrumented Charpy testing using pre-cracked specimens is accepted in the majority of textbooks on materials testing and fracture mechanics for education in engineering disciplines. Honoring 100 Years of Charpy testing, a special issue of the *Journal Materialwissenschaft und Werkstofftechnik* was published (Blumenauer 2001).

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Appendix A

Table 1. Milestones in material testing

Year	Event
1495	tensile testing of wires (Leonardo da Vinci)
1638	testing of beams loaded in bending (Galileo Galilei)
1675	testing of elongation of springs (Robert E. Hooke)
1680	elastic deformation of beams (Emde Mariotte)
1696	definition of virtual deformation (John Bernoulli)
1744	description of the shape of elastically deformed beams (Leonard Euler)
1773	determination of the load capacity of beams loaded in bending (Augustin Columb)
1775	registration of the load-deflection diagram of woods beams (Francois Buffon)
1781	patent of the steam engine (James Watt)
1788	systematic mechanical testing of 906 materials (Franz Carl Achard)
1807	definition of the elastic modulus (Thomas Young)
1807	first steam ship (7 October 1807) (Ressel, Fulton)
1822	definition of mechanical stress (Augustin Cauchy)
1825	opening of the first public railway (27 September 1825)
1829	definition of the transverse strain (Denis Poisson)
1837	first publication on fatigue of driving rope
1836	fatigue damage first mentioned in a novel "Mémoires d'un touriste”, by Stendhal
1842	railway accident in Versailles with extensive loss of life
1843	first paper on fatigue tests of railway axles (York, Rankie)
1852	first 100 tonne tensile machine constructed by Werder
1855	new steel making technology (Henry Bessemer)
1856	electric resistance of wires and their lengths (Lord Kelvin)
1858	opening the first material testing laboratory (D. Kirkaldy)
1858	first paper by Wöhler
1864	first metallographical investigation (Henry Clifton Sorby)
1870	Wöhler`s material selection and design system against fatigue of railway axles
1871	foundation of the Laboratory for Mechanical Technology in Munich (J. Bauschinger)
1873	foundation of the Laboratory for Mechanical Technology in Vienna (K. von Jenny)
1874	foundation of the Laboratory for Mechanical Technology in Budapest
1879	Material Testing Laboratory (MPA) in Zurich (L. v. Tetmajer)
1880	optical microscope by Martens with magnification of 200x (A. Martens)
≈1881	Bauschinger-effect ⇒ low cycle fatigue
1884	1st Bauschinger Conference on Material Testing in Munich
1886	2nd Bauschinger Conference on Material Testing in Dresden
1890	3rd Bauschinger Conference on Material Testing in Berlin
1891	foundation of the Commission des méthodes d’essai des matériaux de construction (by decree of the French President)
1893	4th Bauschinger Conference on Material Testing in Vienna
1895	1st Congress of the International Society for Testing of Material (ISTM) (L. Tetmajer, Zurich, 9-11 September) (5th Congress)
1895	discovery of X-rays by W. C. Röntgen
1896	foundation of the German Society for Material Testing (President: A. Martens)
1896	demonstration of X-ray testing in New York at the National Electrochemical Exhib.
1898	establishment of the American Society for Testing of Materials (ASTM)
1900	hardness testing method by Brinell
1904	observation of the upper and lower yield stress (Carl v. Bach)
1906	4th Congress of the ISTM in Brussels (8th Congress)
1907	stress distribution at the vicinity of sharp notches and cracks (K. Wieghardt)
1908	Rockwell hardness testing method
1910	analytical description of stress versus life-time curve (Basquin)
1912	production of stainless steel by the Krupp company
1912	X-ray testing of crystalline structures (Max v. Laue)

1912	new testing machine for alternating load tests, (B.P. Haigh)
1913	stress distribution at the vicinity of sharp notches, crack (C.E. Inglis)
1917	foundation of the German Standards Association (DIN)
1919	first creep test (P. Chevenard)
1920	energy balance concept for cracks (A.A. Griffith)
1924	concept on fatigue damage at different stress level (Palmgren)
1929	patent of ultrasonic testing for detection of flaws in metals (S.J. Sokolov)
1930	creep test at biaxial loading conditions (R.W. Bailey)
1930	stress concentration and fatigue strength (R.E. Peterson)
1931	determination of the residual stresses by etching of layers (N.N. Davidenkov)
1932	load spectrum measurements for agricultural machines (Kloth, Stoppel)
1934	magnetic testing (W. Gerhard)
1935	introduction of "shape-strength" phenomena (Gestaltfestigkeit) (A. Thum)
1935	notch factor definition in fatigue β_k (A. Thum)
1936	first crack-propagation law (A. V. de Forest)
1937	automatic crack detection equipment (F. Förster)
1937	concept on notch theory (Neuber)
1937	damage accumulation from stress cycles of varying amplitude (B.E. Langer)
1932-38	load spectrum measurements and publication for aircraft (H.W. Kaul)
≈ 1939	introduction of "working-strength" phenomena (Betriebsfestigkeit - Gaßner)
1939	introduction of strain-gauge technology in strain measurements
1939	statistical nature of fatigue (W. Weibull)
1939	introduction of cracks solutions for elastic bodies (Westergaard)
1943	residual stress influence on fatigue (O.J. Horger)
1945	concept in cumulative damage in fatigue (Miner)
1945	thickness measurement with ultrasound (Ewin)
1946	crack solutions for elastic body for different loading conditions (I.N. Sneddon)
1951	foundation of International Committee on Aeronautical Fatigue
1953	low-cycle-fatigue at NACA/NASA (S.S. Manson)
1953	random fatigue (A.M. Freudenthal, E.J. Gumbel)
1954	low-cycle-fatigue at General Electric (L.F. Coffin)
1954	de Havilland Comet airplane accidents (Elba on 10/01 and near Naples on 8/04)
1956	non-linear Corten-Dolan approach on cumulative fatigue damage
1956	concept of crack extension force at NRL (G.R. Irwin)
1959	introduction of the DGS diagram (J. Krautkrämer)
1959-62	Crack-tip cohesive model (G.I. Barenblatt, Panasyuk, Dugdale)
1959	determination of the size of flaws using ultrasonic testing (J. Krautkrämer)
1960	Electro-hydraulic closed-loop testing machine
1961	Fracture-mechanics-based crack growth law (P.C. Paris, Gomez, Anderson)
≈ 1964	Computer-aided (analogue) material testing system (P. Mast)
1968	introduction of ΔK_{eff}, crack-growth model (W. Elber)
1968	conservation integrals (J. Rice, Cherepanov)
1970	first standard for fracture-mechanics testing (ASTM E 399-70)
1983	first standard for testing of fatigue crack growth (ASTM E 647-83)
1986	application of RS232/V24 to ultrasonic testing equipment
1994	digital ultrasonic testing equipment with built-in DGS diagrams